Monitoring Thermal Treatment Processes Using Electrical Resistance Tomography

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A. Ramirez, Jane Beatty, John Carbino, W. Daily, and R. Newmark

Abstract

We used electrical resistance tomography (ERT) to map in near real-time the subsurface effects of two in situ thermal treatment processes: steam injection and ohmic heating. The subsurface progress of both processes was monitored at a gasoline contaminated site as part of a demonstration of an environmental restoration process known as the Dynamic Underground Stripping Project. We mapped changes in the soil resistivity caused by both thermal processes using a dipole-dipole measurement technique to measure the bulk electrical resistivity distribution in the soil mass. We could detect the effects of steam invasion and ohmic heating by mapping changes in the soil resistivity as a function of space and time. During steam injection, the observed changes in the soil's resistivity in the saturated zone where caused primarily by increases in pore water and soil temperatures and to a lesser extent by changes in liquid saturation and groundwater electrical conductivity. During ohmic heating, the resistivity changes were also caused by temperature increases and liquid saturation changes and by changes in the groundwater's electrical conductivity in the saturated zone. This test demonstrated that ERT tomographs, used in combination with other data such as temperature, can be used reliably by the decision-makers to monitor and control the progress of subsurface remediation.

Introduction

The Dynamic Underground Stripping Project (DUSP) was undertaken by the Department of Energy (DOE) to demonstrate the remedial cleanup of volatile, organic compounds (VOCs) from saturated and unsaturated soil horizons at the

Lawrence Livermore National Laboratory. The DUSP remediation concept combines subsurface steam injection and electrical ohmic heating to remove volatile organic compounds from the saturated and unsaturated soil horizons (Aines, 1991). The ohmic heating phase involved the use of electrical energy to increase the temperature of the least permeable layers where little or no injected steam would penetrate. The steam injection phase involved simultaneously injecting steam into the most permeable layers and extracting liquid and vapor through two vertical wells. We used ERT to monitor changes in the soil's resistivity distribution during the ohmic heating and steam injection phases, conducted at a site contaminated with gasoline.

Our objective was to use ERT periodically to map the changes in resistivity caused by both in situ thermal processes. We would then compare the data sets and examine the changes in the resistivity caused by each of the processes. This information helps us understand the subsurface progress of both thermal processes and the impact of the heterogeneous subsurface environment on the efficacy of remedial action. An accurate understanding of the interaction between each thermal process and the geologic environment is needed to assess the remediation effectiveness. This underground imaging technique substantially reduces the need for the number of boreholes that would otherwise be required to monitor the process.

Previous ERT Work

Ramirez et al., 1993 demonstrated the usefulness of using ERT to map the progress of a subsurface steam flood in an uncontaminated site. This work showed that the injected steam caused readily detectable changes in the formation's resistivity and that resistivity changes could be used as a diagnostic of steam invasion. The work also suggested that, with modest modifications, the ERT technique could produce tomographs within a few hours of the data being collected.

Description of ERT

To image the resistivity distribution between two boreholes, we placed a number of electrodes in electrical contact with the soil in each borehole

(Figure 1). Using an automatic data collection and switching system (shown schematically in Figure 2), we then applied a known current to any two electrodes and measured the resulting voltage difference between other pairs of electrodes. Each ratio of measured voltage and current is a transfer resistance. Next, we switched to two other electrodes, applied current between two other electrodes and again measured the voltage differences using electrode pairs not being used for the source current. We repeated this process until many combinations were measured that completely encircled the target area. For n electrodes, there are $n(n-3)/2$ linearly independent transfer resistances. A complete set of linearly independent data contains the maximum information content about the target; any additional measurements collected are redundant. This formula does not count reciprocal measurements because a measurement and its reciprocal contain the same information and, therefore, are only counted as one by the formula. The reciprocal to any original transmitter-receiver pair is one in which the original transmitter dipole becomes the receiver dipole, and in which the original receiver dipole becomes the transmitter dipole.

Four point measurements were used to eliminate the effect of electrode contact resistance on the measured values of formation resistance. The measurements were made using a direct current (DC) measurement system that switched the polarity of the transmitter voltage and corrected for naturally occurring self-potentials. The DC frequency eliminates inductive coupling between wires connecting each electrode in a borehole to the ground surface. The transmitter-receiver combinations sampled provided a complete set of linearly independent measurements as well as some redundant measurements. The combinations sampled included transmitter-receiver pairs located within the same borehole, transmitters in one borehole and receivers in the other borehole, and combinations that had each pole of the receiver and of the transmitter pair located in separate boreholes.

Calculating the distribution of resistivity in the vicinity of the boreholes, given the measured transfer resistances, is a highly nonlinear problem because the current paths are dependent on the resistivity distribution. This type of inversion has been widely studied by others. For example, Dines and Lytle (1981) used a circuit analysis approach to generate estimates of the conductivity using an iterative process on network equations that are linearized in the unknown conductance variables. Other researchers in the medical and geophysical arena have tried different approaches with varying degrees of success [(e.g., Henderson and Webster (1978), Pelton et al. (1978), Nariida and Vozoff (1984), Kohn and Vogelius (1987), Wexler et al. (1985), Brown et al. (1985), Isaacson (1986)]. Recent work by Berryman and Kohn (1990) showed that using variational constraints can stabilize the inversion.

Forward Solution:

The ERT inversion process involves solving both the forward and inverse problems. The solution to the forward problem uses the finite element method (FEM) to compute the potential electrical response of a two-dimensional earth due to a three-dimensional source. To avoid the difficulty of numerically solving a three-dimensional problem, Poisson's equation is formulated in the wave number domain using Fourier transformation in the strike direction. The governing equation is:

$$\frac{\partial}{\partial x}\left(\sigma\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial z}\left(\sigma\frac{\partial V}{\partial z}\right)-\lambda^2\sigma V=-I\delta(x)\delta(z) \qquad (1)$$

where V is the potential in the Fourier transform domain, σ is the conductivity, λ is the Fourier transform variable, I is the source current, and $\delta(x)$ is the delta function (Hohmann, 1988). Our two-dimensional FEM algorithm is based on the theory described by Huebner and Thornton (1982), and our implementation of it follows that described by Wannamaker et al. (1987) for modeling two-dimensional magnetotelluric data. Using the FEM, we can calculate the potentials for a discrete number of transform variables at the "nodes" of a mesh of quadrilateral elements. We can then inversely transform the potentials back into the Cartesian domain using the method described by LaBrecque (1989).

Numerical Inversion:

The inverse algorithm iteratively finds the maximum value of a, the stabilization parameter, for which the minimizing the objective function,

$$Y(\mathbf{P}) = c^2(\mathbf{P}) + a\, W(\mathbf{P}), \qquad (2)$$

gives a value of c^2 (**P**) equal to an a priori value where **P** is the vector of unknown parameters, W(**P**) is the stabilizing function (Tikhonov and Arsenin, 1977), and c^2 is the chi-squared statistic. In our work, the a priori value of c^2 is assumed to be equal to the number of data points. The inverted parameters are the natural logarithms of the conductivities of *pixels*. Each pixel contains the elements of a rectangular region of a FEM mesh. The chi-squared statistic is given by

$$(\mathbf{D} - \mathbf{F}(\mathbf{P}))^T \underline{\mathbf{W}}^{-1} (\mathbf{D} - \mathbf{F}(\mathbf{P})) = c^2 \qquad (3)$$

where **D** is the vector of known data values, and $\underline{\mathbf{W}}$ is the data covariance matrix. The roughness operator stabilizes and removes ambiguity in the resistivity inversion by minimizing the model roughness; this is referred to as the smoothest inversion. The roughness operator, W(**P**), is given by

$$W(\mathbf{P}) = \mathbf{P}^T \underline{\mathbf{R}} \mathbf{P}, \qquad (4)$$

where $\underline{\mathbf{R}}$ is the roughness matrix, which is a numerical approximation to the 2-D Laplacian operator (Sasaki, 1990).

At each iteration, our algorithm begins by approximating the forward solution by a first order Taylor's series of the form

$$\mathbf{F}(\mathbf{P} + \Delta\mathbf{P}) \approx \overline{\mathbf{A}}\ \Delta\mathbf{P} + \mathbf{F}(\mathbf{P}). \qquad (5)$$

where $\overline{\mathbf{A}}$ is a matrix of the first derivatives of the data points with respect to the parameters **P**.

Using a root finding algorithm, alpha is estimated for this linearized system. A modified Marquardt method iteration (Bard, 1974) is then used to find the parameters that minimize the objective function (equation 2) for the value of a from the linearized system. Iterations are repeated until the changes in a and c^2 from one iteration to the next are below a tolerance level.

Experimental Procedure

Figure 3 shows a top view of the borehole layout used for this test. Three of the six injection wells are within 1–2 m of planes defined by boreholes TEP10 and TEP6, TEP9 and TEP3, and TEP9 and TEP5. We will label the ERT planes according to the following example: TEP2–TEP9 plane, with borehole TEP2 on the left side of the image and borehole TEP9 on the right. The extraction wells were closest to planes TEP9–TEP10, TEP8–TEP9, and TEP7–TEP9. Each of the boreholes used for ERT measurements contained ten electrodes spaced every 3.66 m (12 ft.) between depths 15.85 m (52 ft.) and 48.77 m (160 ft.). The image plane width is determined by the borehole separations shown in Figure 3; the widths of the image planes ranged from 12.5 m (41 ft.) to 48.3 m (158 ft.).

Details of the ERT borehole completion are shown in Figure 4. The electrodes consisted of sheets of stainless steel 7.6 cm wide and 30 cm long. Each electrode was strapped to the outside of a solid fiberglass casing and was connected to the surface by a multiconductor electrical cable. The annular space between the borehole wall and the casing was backfilled with cement grout to electrically connect the electrodes and the formation. The fiberglass casing provided access to a temperature monitoring probe and an induction probe used to measure electrical resistivity of the sediment immediately adjacent to the borehole wall. The multiconductor cable connected to the electrodes in each borehole was connected to a central junction box; this system allowed the ERT system operator to quickly connect the measurement system to any pair of monitoring boreholes.

Finite Element Mesh

Two finite element meshes were constructed to model the resistivity structure. The two meshes were defined such that the aspect ratio of each element in the region between the boreholes was roughly 1. An aspect ratio equal to 1 results in the most accurate forward problem calculation. Reconstruction planes having a borehole separation smaller than 18 m were modeled with the small mesh shown in Figure 5a; this mesh is 7 elements wide (between the boreholes) and 18 elements wide (along the boreholes). Other elements were used to model the resistivity external to the region between the boreholes although their values are poorly constrained by the data and therefore are not reliable. Reconstruction planes having borehole separation greater than 18 m were modeled with the mesh shown in Figure 5b; this mesh is 12 elements wide (between the boreholes) and 18 elements wide (along the boreholes).

ERT image resolution is a complicated function of many factors including reconstruction pixel size, data signal to noise, electrode and borehole separation, the subsurface resistivity distributions, and the degree to which the resistivity matches the two-dimensional model of the forward calculations. We believe that a reasonable estimate of spatial resolution is provided by what we define as the resolution radius matrix. The resolution radius matrix for each image plane defines the effective area at each point in the plane over which the resistivity distribution is averaged. Clearly, resolution can be no better than one pixel. The resolution matrices for selected image planes are shown in Figure 6. The resolution radius images shown span the range of image aspect ratios and borehole separations of all the ERT planes. In general, these images show that the best resolution (smallest resolution radius) is observed in those planes that have the smallest width to height ratio. For example, note that the plane TEP9–TEP10 exhibits a higher resolution than other planes because the aspect ratio of this image plane is the highest of all the images shown. The images also show that the smallest resolution radii (best resolution) are obtained close to the two side edges of the image where the electrodes were located, and that the longest resolution radii (worst resolution) is obtained along a vertical stripe at the center of the image.

Note that, for the images shown in Figure 6 (and in subsequent tomograph figures throughout the report), the vertical scale is shown on the figure. However, the horizontal scale is unique for each image because the horizontal/vertical cell aspect ratio shown in Table 1 is typically not equal to 1.0. To obtain the correct width for any image, an apparent image width can be determined using the vertical scale shown in the figure; this apparent width needs to be multiplied by the cell aspect ratio for each plane shown in Table 1 to obtain the correct width dimension.

Near-Real-Time Imaging

A key requirement placed on all the monitoring systems used in this project was that data be available in near-real time because the monitoring data were used

Table I. The distances between adjacent boreholes for the ERT planes monitored. Also shown are the aspect ratios (width to height ratio) of each plane.

ERT plane	borehole separation (ft)	borehole separation (m)	horizontal cell size (m)	vertical cell size (m)	cell aspect ratio (horiz/vert)
SMALL MESH					
TEP7–TEP8	41	12.50	1.79	1.83	0.98
tep8–TEP9	50	15.24	2.18	1.83	1.19
tep9 tep10	45	13.72	1.96	1.83	1.07
tep 10–TEP7	43	13.11	1.87	1.83	1.02
tep 8–TEP10	58.5	17.83	2.55	1.83	1.39
tep 07–TEP02	49	14.94	2.13	1.83	1.17
tep8 tep2	47.5	14.48	2.07	1.83	1.13
LARGE MESH					
tep9tep4	70	21.34	1.78	1.83	0.97
tep8tep3	68.6	20.91	1.74	1.83	0.95
tep2tep11	84	25.60	2.13	1.83	1.17
tep7tep1	71.6	21.82	1.82	1.83	0.99
tep10tep6	90	27.43	2.29	1.83	1.25
tep10tep5	91.6	27.92	2.33	1.83	1.27
tep9tep4	70	21.34	1.78	1.83	0.97
tep9tep7	72	21.95	1.83	1.83	1.00
tep9tep3	78	23.77	1.98	1.83	1.08
tep9tep5	96.5	29.41	2.45	1.83	1.34
tep5tep6	82	24.99	2.08	1.83	1.14
tep6tep1	97.1	29.60	2.47	1.83	1.35
tep1tep11	158.5	48.31	4.03	1.83	2.20
tep11tep3	152.5	46.48	3.87	1.83	2.12
tep3tep4	94	28.65	2.39	1.83	1.31
tep4tep5	113.6	34.63	2.89	1.83	1.58

to make process control decisions on a daily basis. The ERT data-collection and data processing systems were automated as much as possible to meet the requirement of near-real-time availability of tomographs. Figure 7 summarizes the key components of the ERT systems used for this work. During normal operations, these systems produced a tomograph within 20 minutes of the completion of data collection. The system required one full-time technician to operate the data collection system and transmit the data to a processing workstation; a part-time data analyst monitored the data-processing system, identified any problems with data quality (e.g., problems caused by broken cables, data with excessive levels of noise), and prepared the tomographs for final interpretation. With modest modifications to this system, data collection and data processing could both be performed by a single full-time individual.

Geologic Setting

The description that follows is adapted from Bishop et al. (1992). The site is underlain by Pliocene to Holocene lacustrine and alluvial sedimentary deposits. The upper 52 m (170 ft.) of these sediments consist of approximately 60% fine-grained sediments (clay and silt), and 40% coarse-grained sediments (sand and gravel). Because of the complex interfingering of different sediment types that occur in an alluvial depositional environment, multiple sediment types exist at similar depth intervals in different boreholes. The upper part of the lithologic sequence consists of late Pleistocene to Holocene alluvial deposits consisting of complexly interbedded clay, silt, sand, and gravel. Below this sequence, the Plio-Pleistocene Livermore Formation at the site is found starting between depths 24.5 m (80 ft.) to 35.5 m (116 ft.). The upper member of the Livermore Formation was encountered by the monitoring boreholes; this unit consists of approximately equal amounts of sand, gravel, silt, and clay.

Results and Discussion of Baseline Electrical Resistance Tomographs

Comparisons of Baseline Tomographs vs. Lithologic Logs

Figures 8a and 8b show the absolute images representing the (baseline) resistivity values prior to the start of ohmic heating. These images are compared with lithologic logs obtained for all of the ERT monitoring boreholes. The lithologic logs are based on visual inspections of soil cores. A common color scale is used to depict the ERT tomographs. A logarithmic scale is used to represent resistivity due to the wide range of resistivity values measured. The warmer colors (red and yellow) depict regions of higher resistivity, whereas the cooler colors (blue and purple) depict regions of lower resistivity. Note that the layers close to the two side edges of each image in Figure 8 appear thicker than the same layers near the image center. This apparent thinning toward the middle of the images is an artifact of decreases in resolution toward the midpoint of the images.

The ERT tomographs and induction surveys show two regions of high resistivity. The depth to the top of the lowest high-resistivity region ranges between 34 m (112 ft.) and 39.6 m (130 ft.) depths; the thickness of this lower unit is typically between 2.1–5.8 m (7–19 ft.) (Noyes, 1994). This region of high resistivity extends throughout the whole site and correlates with a gravel layer identified in the lithologic logs; we will refer to this zone as the "lower steam zone." Noyes (1994) suggests that this zone represents a braided stream deposit, which is relatively homogeneous and forms a laterally continuous sheet-like deposit; also, Noyes indicates that this zone exhibits good lateral hydraulic connectivity.

Another region of relatively high resistivity can be observed above the lower steam zone; this region appears to be intermittent throughout the site. We will refer to this region as the "upper steam zone." The top of this zone generally occurs between 23–29 m (75–95 ft.), and its thickness ranges from 0–9 m (0–30 ft.). Noyes (1994) describes this zone as a heterogeneous mixture of lens-shaped channel deposits containing high-to-lower permeability, sandy to clayey gravels and silty sands. These deposits are hydraulically connected where overlying higher permeability units incise underlying higher channel deposits.

Between the upper and lower steam zones, there is a region of lower resistivity between the depths of 32 and 37 m. A sequence of clays and silts corresponds to this low resistivity region. This region acts as a confining layer hydraulically separating the upper and lower steam zones (Noyes, 1994). Noyes indicates, based on hydraulic testing results, that there is no communication between the upper and lower steam zone, indicating that the confining zone forms a laterally continuous barrier.

Comparisons of ERT images and lithologic logs suggest that a continuous gravel layer exists at depth (lower steam zone), above it is a less permeable sequence of silts and clays (layers targeted for ohmic heating), and above that there is an intermittent sequence of gravels and sands (upper steam zone). The higher permeability units are typically the most electrically resistive, whereas the least permeable units exhibit the lowest electrical resistivity.

Effects of Saturation and Mineralogy on Resistivity Distribution

The resistivity distributions shown in Figure 6 do not appear to be indicative of the water table location (water table depth is approximately 31.4 m (103 ft.)). There are two reasons for this: 1) the specific conductance of the native groundwater is a relatively low 9.0×10^{-2} S/m (Jovanovich et al., *this report*), and 2) most of the layers present have clay minerals. Some clay minerals increase electrolytic conduction by adding pathways of electrical conductivity in addition to the path through electrolyte solution in the pore space. Clay particles possess a net negative charge that is compensated by an excess number of cations in solution close to clay surfaces (Hearst and Nelson, 1985). The cations/clay interface form a "double layer" along which conduction occurs in addition to conduction through the electrolyte. This phenomenon tends to dominate any correlation between water saturation and resistivity when the resistivity of the groundwater is high.

Difference Tomographs

Using the ERT algorithm previously described, we constructed difference tomographs of the resistivity distribution in the plane between each pair of boreholes. These tomographs represent changes in resistivity relative to initial conditions (i.e., the tomographs are generated by subtracting values of pixels in one tomograph from values of pixels in an earlier tomograph). These difference tomographs should show only those features that have changed between the time the two data sets were taken. The difference tomographs are compared with temperature logs and lithologic logs obtained along most of the boreholes used for ERT measurements. The temperature data were collected using both fixed thermocouple and movable temperature probes. We will only discuss a small subset of the hundreds of tomographs collected daily over a period of several months.

Resistivity Changes Caused by Steam Injection—First Steam Pass

Figures 9, 10a, and 10b summarize the steam injection schedule used during the first and second steam injection cycle. The figures indicate the time periods during which the various wells were in use for steam injection and their location relative to the various ERT monitoring planes.

We first look at resistivity changes that developed near three of the six injection wells during the first steam pass. Figure 11 shows a time sequence of difference resistivity tomographs for planes in close proximity to the steam injection wells; the time sequence begins with the fist day of the first steam pass (labeled as day 1), and ends on the last day of the first steam pass cycle (day 36). The time sequence labeled TEP10–TEP6 represents resistivity changes along a plane defined by borehole TEP10 (along the left side of each image on the first row) and by borehole TEP6 (along the right side of each image on the first row). The other two rows of images correspond to time sequences along two other planes. The images are compared against formation lithologic logs obtained along the same boreholes where the ERT electrodes were located. For all images shown, the color scale representing resistivity change has been plotted with the same color scale for ease of comparison. Note that resistivity decreases (relative to pre-injection conditions) are shown by colors cooler than orange, a zero change in resistivity is represented by the color orange, and a increase in resistivity is shown by a red color.

During the first few days of steam injection , all three time sequences in Figure 11 show resistivity decreases that increase in magnitude and extent with time. The early part of the sequence also shows that the resistivity changes grow preferentially in one direction; for example, the TEP10–TEP6 time sequence shows (on days 1, 2, and 4) that the changes toward TEP10 are larger than toward TEP6 even though the injector is near the middle of the image. As shown in Figure 3, TEP10 is located toward the extraction wells, whereas TEP6 is located away from the extraction wells. Similar observations can be made for the TEP3–TEP9 and TEP9–TEP5 sequences. These three time sequences, show that during the early part of the injection cycle the biggest resistivity differences generally occur toward the extraction wells rather than away from them. This pattern suggests that most of the injected steam flowed radially inward toward the extraction well rather than radially outward. This behavior indicates that the extraction system had some influence in the preferred direction of flow in both the vadose and saturated zones. This behavior was required to ensure that contamination was pushed toward the extraction wells and not away from them. Verification of this behavior was very important to allow the continuation of the injection process.

Figure 11 can also be used to evaluate the degree of hydraulic isolation between the lower and upper steam zones in the vicinity of the injector wells. The early part of the TEP10–TEP6 sequence shows that the resistivity changes by and large are constrained to the lower zone at a depth of about 35 m (note that the apparent thickening of the resistivity changes with time is an artifact of the gradients in resolution radius described earlier). This behavior suggests that the lower steam zone appears to be well isolated from the upper steam zone during the time when only the lower steam zone was being treated. The TEP3–TEP9 and TEP9–TEP5 time sequences show contrasting behavior, i.e., resistivity changes are observed along a significantly wider depth range between 25 and 40 m. This behavior points to possible leakage from the lower steam zone to the upper zone when only the lower injectors were in use. The leakage may have been caused by the failure of seals installed in the injection wells or by the presence of undiscovered fluid pathways in the confining layer between the upper and lower steam zone.

We now look at the resistivity differences that developed near the center of the injection pattern close to the extraction wells. Figure 12 shows resistivity differences as a function of time for three ERT planes (TEP8–TEP9, TEP9–TEP10, and TEP10–TEP7). As expected, the center of the injection pattern showed most of the largest resistive changes observed. Beginning with the "Day 2" images of Figure 12, we see that the biggest changes develop in the vicinity of well TEP10 at a depth of approximately 38 m. It is interesting that well TEP10 shows the greatest change, given that it is farther from any of the injection wells than TEP9 (see plan view in Figure 3 for distances to injectors). There are also small resistivity changes observed in the upper steam zone although steam was only being injected in the lower zone at this time. The "Day 10" images show growth in the magnitude and extent of the receptivity differences in both steam zones although only the lower zone injectors are in use. The greatest lower zone changes occur near TEP8, 9, and 10, whereas changes near well TEP7 are significantly smaller; this pattern continues at Day 20. Also large resistivity decreases develop in the upper steam zone after the upper injectors are used for the first time (Day 14). The biggest changes develop around TEP8 and 9, whereas the smallest changes occur toward TEP7. These three planes exhibit time behavior typical of almost all of the planes monitored; i.e., decreases in resistivity developed across each plane as steam injection continued. These changes were concentrated in gravel and sand layers that make up the upper and lower steam zones. The changes increased in magnitude as steam injection progressed. We believe that the observed decrease is due to the following conditions: A) As the steam front approaches the area, increases in the groundwater temperature result in bulk resistivity decreases due to increases in exchange cation mobility in clay minerals, and to a lesser extent to increases in ion mobility for ions within the free electrolyte; in the upper steam zone, the steam flood also caused increases in moisture content that contributed to the resistivity decrease. B) Later, as the steam front penetrates the initially saturated lower steam zone, additional decreases in bulk resistivity occur as temperatures climb above the boiling point; bulk resistivity decreases due to greater exchange cation mobility more than make up for the resistivity increase expected as a result of water saturation decreases as steam displaces pore water. The arguments supporting this interpretation will be discussed later under the subsection "Relative effects of temperature, water saturation, and fluid conductivity on resistivity changes caused by steam injection."

Figures 13 and 14 show difference resistivity tomographs at the end of the first steam cycle for all the planes monitored on a regular basis. The figures also show lithologic columns and temperature surveys obtained for the corresponding wells. The injected steam temperature was about 115°C (Siegel, *this report*) The temperature data shown in Figures 13, 14, and in subsequent figures were selected from measured temperatures. All images in these figures show that regions of resistivity decrease in the depth range of 37 to 40 m (lower steam zone). The lithologic logs indicate that a laterally continuous gravel layer is present at these depths, extending throughout the whole site. All planes also show large resistivity decreases in the upper steam zone between 20 and 33 m of depth. We interpret these resistivity decreases as indicative of the effects of steam or warm water invading the gravel layer.

Note that temperature logs and ERT images show that the steam appears to be vertically constrained by the upper and lower contacts of the unit previously defined as the confining zone. In the depth range between 34 to 37 m, the lithologic logs show the presence of silt/clay layers. For example, planes TEP8–TEP10, TEP9–TEP10, TEP10–TEP7, and TEP7–TEP2 show small resistivity differences and temperature increases between depths of 35 and 37 m. The clay/silt layers within this unit have hydraulic conductivities that are much smaller than those of the gravel/sand layers on either side of the confining unit (Noyes, 1993). This region was the farthest removed from the injection wells thereby requiring more time and steam volume to reach a given temperature than other regions. Contamination present within the cold spot may have remained undisturbed by the steam flood and remained trapped within the confining zone.

Relative Effects of Temperature, Water Saturation,
and Fluid Conductivity on Resistivity Changes Caused by Steam Injection

Interpretation of the ERT results during ohmic heating is complicated by the fact that simultaneously, several process are causing changes in resistivity. The principal processes of interest are heating of the formation and pore water, changes in liquid saturation, and changes in the electrical conductivity of the groundwater. Higher temperatures mean increased ion mobility for both surface charge and electrolytic ions, which reduces the bulk resistivity of the formation. Higher liquid saturations and higher groundwater electrical conductivity also reduce the bulk resistivity because there are greater numbers of ions to transmit electrical charge. A unique interpretation of resistivity images is not possible because several different mechanisms are at work to change resistivity. However, we combined ERT with the other geological, process, and geophysical data in an effort to generate a meaningful interpretation of the behavior of the formation during steam injection.

The ERT tomographs show that the resistivity decreased relative to pretest values as the steam penetrated the gravel layer between depths of 35–40 m. Steam is very resistive and can cause resistivity increases as it displaces groundwater. Ramirez et al., 1993 suggested that the resistivity decreases associated with steam injection are caused by the large increases in temperature caused by the steam and, to a lesser extent, by changes in saturation and specific conductance of the water remaining in the pore space.

In this paper, we use an approach similar to that previously described by Ramirez et al., (1993) to estimate an upper bound for gas/liquid saturations during steam injection. Our analysis is only applicable to the lower steam zone. The analysis requires that the pre-injection liquid saturation be known with certainty; good estimates of pre-injection saturation are only possible for the lower steam zone because it is located in the saturated zone.

The work of Waxman and Thomas (1974) shows that clay conductance contributes a significant fraction of total conductance under some conditions and modifies the saturation - porosity - water - resistivity relationship. The effects become more significant with increasing clay content, decreasing S_w, and increasing R_w. The model proposed by Waxman and Thomas assumes: 1) a parallel conductance mechanism with free electrolyte and clay-exchange cation components, and 2) an exchange cation conductance B that depends on the equilibrating electrolyte concentration and temperature. At a fixed temperature, B approaches a maximum value for low R_w and a minimum value for high R_w. These ions provide a conductor for electrical current separate from, but parallel to, the conduction path through the pore space. We use this model to estimate the effects of steam injection on liquid/gas saturations at the end of the first steam pass (3/11/93).

The steam invasion zone was constrained to a gravel layer with a pre-injection bulk resistivity of about 45 ohm-m, with the fluid resistivity being about 11 ohm-m [specific conductance of 9×10^{-2} S/m (from Jovanovich et al., *this report*)]. Core samples show that the cation exchange capacity of the lower steam zone varies, ranging from about 4 to 16 meq/100g of sediment. These values indicate that the native groundwater is fairly resistive, and that a significant portion of the electrical conductivity may be due to exchangeable cations in the gravel layer.

Chesnut and Cox (1978) derived the following formula from the Waxman and Smits model:

$$R_t = \frac{(\phi S_w)^{-v} R_w}{1 + R_w B Q_{vb} (\phi S_w)^{-1}} \qquad (1)$$

where:
R_w = water resistivity, ohm-cm
R_t = resistivity of water bearing sediment (or rock), ohm-cm
ϕ = fractional porosity
S_w = water saturation as fraction of pore volume
B = equivalent conductance of exchangeable cations,
(cm^3/meq)/(ohm-cm)
Q_{vb} = cation exchange capacity of sediment, meq per cm^3 of bulk volume
v = combined saturation and porosity exponent, typically about 2

Waxman and Thomas used the parameter Q_v, which is the cation exchange capacity per unit pore volume, instead of Q_{vb}. Substitution of $Q_{vb} = \phi Q_v$ into the original form of the Waxman-Smits equation, and assuming that the saturation exponent m, and that the porosity exponents n are equal, allows terms involving porosity and saturation to be expressed with the combination ϕS_w instead of as separate parameters.

Measurements of cation exchange capacity Q_m are usually reported as meq per 100 grams of dry sediment (or rock). The parameter used in the equation above is easily calculated from the equation:

$$Q_{vb} = Q_m (1 - \phi)\, \rho_g/100 \qquad (2)$$

where ρ_g is the grain density of the sediment in grams per cubic centimeter.

For the case of the gravel layer at the experimental site, we have a fairly high R_w and "dirty" (i.e., high clay content and a fairly large cation exchange capacity) sediments, for which the second term in the denominator of the modified Waxman-Smits equation is large compared to unity. For large R_w, the exchange-ion conductance term, B, approaches 0.17Bmax, which is a function of temperature only.

We can use equations 1 and 2 to solve for the Q_m of the lower steam zone using measured values of R_w, ϕ, S_w, and R_t. We use the following values: R_w = 11 ohm-m, ϕ = 0.37, S_w = 1.0 (these parameter values were selected from Jovanovich et al., *this report*) and R_t = 45–50 ohm-m. Rearranging terms in equations 1 and 2 and solving for Q_m, we calculate that Q_m = 2.4 to 3.7 meq/100 cc. These calculated values are in the low end of the range of cation exchange capacities measured on core samples.

We can only speculate as to why the calculated Q_m values based on resistivity measurements are small relative to the core sample values. One hypothesis is that the core sampling process tends to provide core samples that are richer in clay because the core recovery improves as the sample clay content increases. Such samples would tend to provide relatively high Q_m values because Q_m generally increases with increasing clay content. Clay-poor samples such as clean sands and gravels tend to suffer poor core recovery because there is little or no clay binding the individual grains. To evaluate the hypothesis that the poor agreement in laboratory-measured Q_m and in situ Q_m based on resistivity may be caused by a sampling bias, we calculated Q_m values based on resistivity measurements for a clay layer and compared them to the laboratory-measured Q_m values. For this analysis, we selected the following property values from Jovanovich et al., (*this report*.): the cation exchange capacity of the soil is 17.7 meq/100 g of soil, porosity is 0.45, grain density is 2.77 g/cc, and the initial electrical conductivity of the groundwater is 11 ohm-m. Our analysis uses a 10 ohm-m resistivity for the clay layer (based on the clay layer resistivity shown by the baseline ERT tomographs). Using equations 1 and 2 and solving for Q_m, we calculate that Q_m = 18 meq/100 cc. This estimate shows that Q_m

based on resistivity compares favorably with the 17.7 meq/100 g of soil reported by Jovanovich et al., (*this report*) and suggests that the sampling bias hypothesis is plausible. A second hypothesis is that the model used to calculate Q_m from measurements of R_t may yield erroneous results because it neglects clay -hydrocarbon interactions that can affect cation exchange phenomena.

Equation 1 can also be used to estimate the minimum liquid saturation (maximum gas saturation) of the lower steam zone, if the temperature, Q_m, R_w, ϕ, and R_t are known. Figure 15 shows the results of calculations done using equation 1 to estimate the relationship between resistivity differences, temperature, and water saturation. The assumptions made for this analysis are as follows. 1) The pre-injection S_w is 1.0. 2) Q_m is 2.4 meq/100 cc (we chose the value based on R_t to maintain internal consistency with the resistivity measurements). 3) Q_m is constant in space and time as gasoline is removed by the steam injection process. 4) The R_w of the liquid phase removed by the extraction wells provides a reliable measure of the R_w of the water remaining in the pore space; the R_w of the liquid phase changed from 11 (prior to steam injection) to 29 ohm-m at the end of the first steam pass. The analysis also assumes that R_w changes instantaneously everywhere in the lower steam zone from 11 to 29 ohm-m as soon as steam injection starts. Water conductivity measurements of the extraction well effluent showed that the water conductivity changed as assumed. 5) The temperature effects on R_w can be approximated by the following relationship from Pirson (1963):

$$\frac{R_w(T_2)}{R_w(T_1)} \cong \frac{T_1}{T_2}$$

where T_1 and T_2 are temperatures in °F. 6) The resistivity differences are calculated by substracting the pre-injection resistivity at ambient conditions from the perturbed resistivity at higher temperatures and lower S_w.

Figure 15 can be used to make some general observations regarding the effect that various events had on the measured resistivity differences. The figure shows that both positive and negative resistivity differences are possible. The ERT tomographs show that steam injection invariably caused negative resistivity differences in the lower steam zone. Negative resistivity differences in Figure 15 occur only when the water saturation exceeds 0.5 when the formation temperature was 100°C or higher. Thus, we estimate that the liquid saturation of the lower steam zone during the first steam pass had to be equal to or greater than 0.5.

As steam penetrates a region, the temperature increases while the water saturation decreases as steam displaces pore water aside. Figure 15 clearly shows that both the temperature and saturation changes had significant impacts on the resistivity differences measured. However, the temperature increases had the opposite effect of S_W decreases. Note that as temperature increases the resistivity differences become more negative. Decreases in S_W caused by steam invasion cause the resistivity differences to grow more positive. So, as steam penetrates a region, the resistivity decreases caused by increasing the temperature have to be larger than the resistivity increases caused by reductions in S_W in order for the resistivity difference to remain negative. Therefore, we conclude that over the range of temperature and saturation changes caused by steam injection, the effects of temperature were significantly greater than those of saturation changes.

The change in R_W had a relatively small impact on the resistivity differences. The curve labeled "water saturation = 1.0, no change in fluid conductivity" shows the resistivity differences that would result if the R_W of the pore water remained at the initial value of 11 ohm-m (at 20°C). This curve can be compared with the curve labeled "water saturation = 1.0," which assumes that the R_W of the pore water did change from 11 to 29 ohm-m (both at 20°C). Note that the curves show similar resistivity differences at a temperature of 100°C. Therefore, we believe that decreases in R_W play a minor role in decreasing the resistivity when compared to temperature increases and saturation decreases.

Estimates of Liquid Saturation and Extent of the Steam Flood at the End of the First Steam Pass

We will now combine the curves shown in Figure 15 with the temperature profiles and resistivity differences in Figures 13 and 14 to provide estimates of two steam flood parameters at the end of the first steam pass: residual liquid saturation and the extent of the lower steam zone. These estimates apply only to the lower steam zone due to the reasons described in the previous section. Figure 16 shows estimates of liquid saturation (i.e., s = 0.8) for the lower steam zone using the temperatures and resistivity differences shown in Figures 13 and 14, and the resistivity differences-temperature-saturation curves shown in Figure 15. Also shown is the estimate of the location of the 100°C isotherm during the last day of the first steam pass.

Our discussion first focuses on the estimates of residual liquid saturation shown in Figure 16, i.e., the amount of water left in the pore space after steam has moved in and displaced some of the pore water. These estimates were calculated for each resistivity difference image available at the end of the first steam pass; several estimates were calculated for boreholes used in common with more than one plane. We used the resistivity difference values one column in from the edge of each image instead of the values at the edge because we know from simulations that the values near the image edges tend to be larger than the true value. This analysis makes all the simplifying assumptions made to generate the curves shown in Figure 15. In addition, we assumed that the residual saturation estimate was equal to 1.0 wherever the temperature was less than 100°C.

The residual saturation estimates for the boreholes near the center of the injection pattern show significant scatter thereby indicating a significant degree of uncertainty. The causes of the scatter have not been investigated but we can make some educated guesses. 1) At temperatures of above 100°C, the curves in Figure 16 tend to come together such that a small variation in resistivity difference causes significant change in the saturation estimated. 2) The curves were calculated only for a pre-injection resistivity of 45 ohm-m; we know that there was some lateral variability in the initial resistivity of the lower steam zone. Because of the scatter, we suggest that the saturation estimates shown are only rough estimates. Note that the minimum liquid saturation is 0.6 (gas saturation = 0.4) while most values fall in the range of 0.7–0.9 (gas saturation = 0.1 – 0.3). Also note that the region around TEP7 appears to have a residual saturation in that the steam flood did not penetrate this area.

We now focus on the estimate of the location of the of the 100°C isotherm during the last day of the first steam pass as shown Figure 16. This estimate shows the approximate extent of the steam zone. We constructed this estimate as follows. Instead of resistivity difference images, we used resistivity ratio images (the "during injection" image was divided by the corresponding "pre-injection" image pixel by pixel). We used resistivity ratio images because they tend to minimize the effect of resolution radius variations across the images. We then generated resistivity ratio - temperature - saturation curves following a process similar to the one followed for resistivity difference curves. The resistivity ratio curves showed that a resistivity ratio of about 0.42 was expected wherever a temperature of 100°C and a complete saturation (s = 1.0) existed. Then, we identified locations along each image plane and within the lower steam zone where the value approached 0.42. The approximate location of the isotherm was plotted on the map, and the various points were connected. Because there were several possible ways of connecting the points together, we used the results of the tiltmeter surveys (Hunter and Reinke, 1993) to guide our contouring.

The location of the 100°C isotherm in Figure 16 suggests that most of the region within the injector well ring was under steam flood conditions (i.e., temperatures greater than or equal to 100°C and liquid saturation less than 1.0). Near the center of the injection pattern a couple of pockets appear not to be under steam flood conditions. One pocket is near the extraction wells, and the other one is to the North and West of TEP7. The region in the near vicinity of the extraction wells was under the influence of a vacuum, which caused the boiling temperature of water to be about 82°C. This condition probably kept the temperatures near the extraction well below 100°C and caused the apparent "no steam pocket." Note that this formation within this pocket would indeed contain steam but at temperatures below 100°C. The North-South trend of this pocket suggests that the regions of influence of the extraction wells trends the same way. Hydrologic testing done by Noyes (1994) prior to steam injection in the extraction wells suggested that the preferred flow in the lower steam zone occurred also in the North-South direction.

A second "no steam pocket" is shown to the North and East of well TEP7. An isopach of the lower steam zone by Noyes (1994) shows that the formation is relatively thin in this area. The isopach map suggests that this region near TEP7 offers more resistance to steam flow than other portions of the lower steam zone because its decreased thickness would reduce its transmissivity.

Another interesting feature of the steam zone map shown in Figure 16 is the lack of penetration of the steam flood to the NW of injector wells GIW818 and 819. One possible reason for this behavior is that the isopach map suggests that the lower steam zone becomes thinner in this direction. We also know that GIW819 maintained the smallest injection rates of all the injection wells (Siegel, *this report*). The penetration of the steam flood to the North and East of GIW 820 is significantly larger than that observed near GIW818 and 819. The isopach map shows that the lower steam zone is thickest in this area, and that it thickens to the NE. Thus, the steam zone map in Figure 16 appears to show steam flow directions that are consistent with those that might be inferred from the isopach map. The extent of the steam flood near GIW 813 and 814 cannot be estimated as well as in other areas because ERT data needed for this were not collected during this time.

Resistivity Differences during the Hiatus between the First and Second Steam Passes

Figure 10 shows that between 3/11/93 and 6/02/93 the steam injection and water/gas extraction operations were discontinued due to budget constraints. Figures 16 and 17 show the resistivity differences that occurred during this period of no injection. The differences shown in these figures were calculated relative to March 11, 1993 (the last day of steam injection—first steam pass). During this 2.5-month-long period, we can expect a slight cooling of the upper and lower steam zones.

We will first discuss the changes observed in the vadose zone (0–32 m depths). Figures 16 and 17 show that most of the observed changes are resistivity increases. These increases are probably caused by decreases in temperature and moisture content expected during this time. There are also a few resistivity increases observed. These increases may be caused by thermal conduction of heat from the more permeable layers (where steam invasion occurred) to the impermeable layers that accepted little or no steam.

We now look at the resistivity differences in the saturated zone depths greater than 32 m). Both resistivity increases and decreases are present. We believe that there are at least two physical mechanisms that explain these opposite changes. 1) Significant resistivity decreases are present below the lower steam zone between depths of 40–45 m along wells TEP9, 7, and 10. The impermeable units around the lower steam zone increased in temperature as heat moved down-gradient from the high temperature, lower steam zone to the cooler impermeable units. Also, resistivity decreases in the permeable layers can be caused by increases in liquid saturation of the permeable units as hot water replaced steam in the pore space; hot water has a much lower electrical resistivity than steam. 2) Within the lower steam zone, significant resistivity increases are present along TEP7, TEP4, and TEP10. These changes are probably caused by gradual cooling of the lower steam zone as cooler water gradually moves in and mixes with the original hot water.

Changes during Second Steam Pass

ERT surveys were also used during the second steam pass to monitor the changes caused by steam injection. The injection sequence for the second steam pass is summarized in Figures 10b and 10c. These figures show that the injection sequence involved frequent changes of injectors in an attempt to preferentially "sweep" various parts of the formation. To detect the changes in resistivity caused by the various injector arrangements, the resistivity difference tomographs for the second steam pass were calculated using baseline tomographs obtained just before a change occurred in the injector arrangement.

As discussed previously, the resistivity changes observed during the first steam pass were primarily caused by the large increases in subsurface temperature caused by the steam and, to a lesser extent, caused by liquid saturation changes. When the second steam pass started, however, large portions of the subsurface were already at near-boiling temperatures. Thus, resistivity changes caused by the second steam pass were much smaller than those observed during the first steam pass. Furthermore, changes in water saturation caused by steam invasion became as important to the observed resistivity changes as the relatively small temperature increases caused by the second steam pass.

Figures 19 and 20 present the ERT difference tomographs showing the resistivity differences caused by the second steam pass. The differences shown in these figures were calculated between tomographs collected June 29 and 30, 1993 (the last days of steam injection—second steam pass) and tomographs collected just prior to the start of the second steam pass. The difference tomographs are compared against temperature data collected on June 30, 1993. Note that the observed range of resistivity differences is much smaller than the range during the first steam pass. Also note that both positive and negative resistivity differences are present. During the first steam pass, the negative differences were generally much larger in magnitude than the positive differences. The positive and negative differences of the second steam pass show roughly the same magnitude primarily because changes in water saturation became as important to the observed resistivity changes as the relatively small temperature increases caused by the second steam pass.

The tomographs in Figures 19 and 20 show that the second steam pass primarily caused resistivity decreases in the vadose zone (upper steam zone). These resistivity decreases are probably caused by increases in temperature, and by increases in moisture content as steam invaded the partially saturated upper steam zone.

The figures also show the resistivity differences observed in the lower steam zone. Note that the lower steam zone showed both positive as well as negative resistivity differences. The resistivity decreases (negative differences) were probably caused by further increases in formation temperature (from near boiling to above-boiling temperatures) as a result of steam invasion. The resistivity increases (positive differences) could be caused by at least two mechanisms: 1) steam displacing hot water and reducing the liquid saturation of the initially water-saturated lower steam zone, or 2) cooler water penetrating the outer perimeter of the lower steam zone due to the pumping action in the extraction wells. The temperature survey data can be used to infer which of these two mechanisms is likely to be affecting the lower steam zone.

Above-boiling temperatures are required to make Mechanism 1 plausible. Mechanism 2 requires temperature decreases.

Positive resistivity differences occur near wells TEP1, 2, 5, 8, 9, 10, 11. The temperature logs show that the lower steam zone had above boiling temperatures in all boreholes except TEP3, TEP4, TEP6, and TEP11. The positive differences near TEP11 shown in planes TEP2–TEP11 and TEP11–TEP3 are probably caused by cooler water penetrating the outer perimeter of the lower steam zone because the temperatures in this area are well below boiling. However, positive resistivity differences near perimeter wells TEP1 and TEP5 are probably caused by reductions in liquid saturations caused by steam invasion; the temperature surveys from these boreholes show above boiling temperatures especially near TEP1.

Negative resistivity differences in the lower steam zone can be observed on planes near wells TEP7 and 8 on planes TEP7–TEP2, TEP7–TEP8, TEP8–TEP2, and TEP8–TEP3. This may seem surprising given that the temperature profiles show above-boiling temperatures. As pointed out earlier, positive resistivity differences were observed in most other planes having above-boiling temperatures. Temperature surveys taken before the start of the second steam pass show that the lower steam zone temperatures for TEP7 and 8 were approximately 71°C and 82°C, respectively. These temperatures were significantly lower than those in TEP9 and 10 (the two other monitoring wells near the center of the pattern), which showed temperatures of 93°C.

We now use equation 1 to evaluate whether the negative resistivity differences could have been caused by the lower initial temperatures near TEP7 and 8. Figure 21 shows the results of calculations assuming initial lower steam zone temperatures of 75°C (Fig 21a) and 95°C (Fig 21b). These calculations assume that the electrical conductivity of the groundwater remained unchanged except for temperature effects. Comparing these two graphs at a given liquid saturation, we observe that the resistivity differences are more negative for the lower initial temperature of 75°C. For example, a comparison of the 0.8 saturation curve at 115°C shows that a positive 3.2 ohm-m difference in Figure 21a and a negative 2.5 difference in Figure 21b. These calculations suggest that both positive and negative resistivity differences may be indicative of steam invasion when the initial temperatures of the formation are significantly different.

Resistivity Changes during Ohmic Heating

In this subsection, we discuss the ohmic heating phase after discussing the steam injection phase to take advantage of some of the calculations and interpretations developed in the steam phase section.

Interpretation of the ERT results during both ohmic heating and steam injection is complicated by the fact that, simultaneously, several process are causing changes in resistivity. The principal process of interest during ohmic heating is the heating of formation and pore water; in addition, the formation around the electrode is heated enough to result in drying of the formation and affects the resistivity differences measured. Electrode temperatures are high enough at some electrodes that steam is generated from added water or from formation water thereby increasing resistivity near the electrodes.

Figure 22 shows the results of calculations using equation 1 for the case of the clay layer being heated by the ohmic heating process. For this analysis, we selected the following property values from Jovanovich et al., (*this report*): the cation exchange capacity of the soil is 18 meq/100 g of soil, porosity is 0.45, and the initial electrical conductivity of the groundwater is 11 ohm-m. The analysis also assumes that: 1) the initial resistivity of the clay layer is about 10 ohm-m (this value is based on the clay layer resistivity shown by the baseline ERT images in Figures 8a and 8b), 2) the liquid conductivity of the groundwater in the clay is constant during ohmic heating (except for temperature effects), and 3) the initial saturation of the clay is 1.0 because it is located in the saturated zone. The model results in Figure 22 show that both positive and negative resistivity differences may be expected. Increasing temperature by itself is expected to decrease the initial resistivity and result in negative differences. Formation drying (caused by heating) by itself will result in positive differences. Loss of electrolyte leads to increased resistivity, and this effect will eventually overcome the drop in resistivity caused by ion mobility. This drying will not only influence the ERT images but will also restrict heating current flow, which creates the need to add water to the electrodes.

The baseline images of electrical resistivity are shown in Figure 8. The resistive zones correspond to the more permeable sands and gravels, whereas the conductive zones are the silts and clays. Notice that heating electrodes were placed at levels so as to be within certain clay-rich layers that were the target of heating. A lower set of electrodes were positioned at about 35-m depth in H1, H2, and H3. Likewise, an upper set of electrodes were place in these holes at about 22-m depth. All the GIW wells were completed with one lower electrode centered at about 35-m depth. Buettner and Daily (*this report*) describe additional details of the ohmic heating phase.

Figures 23 and 24 show the changes in resistivity for most of the baseline planes on December 14–15 (approximately 34 days into heating) and January 20–21 (right after heating stopped), respectively. The vadose and saturated zones cannot be separated hydraulically, electrically, or thermally. However, for simplicity, we will separately discuss the results from below the water table and those from above the water table.

Saturated Zone by Mid-December

By mid-December, definite anomalies of both increasing and decreasing resistivity had occurred below the water table. In all three planes common to TEP9, there is a strong increase of resistivity as high as 10 ohm-m, 2 or 3 m thick, and centered at about 35-m depth. Note that this resistivity increase occurs below the water table, and corresponds in depth and vertical extent to the target silty clay formation in which the lower electrodes were placed. On the basis of the curves shown in Figure 22, this resistivity increase is interpreted as the drying of that formation caused by heating. By this time, a total of about 31 kWh electrical had been delivered to HW2 lower, GIW819, and GIW818, all within about 40 ft of each other. The images are consistent with a portion of this silty clay dehydrated about 30 ft in size. (At this early time there is no evidence in the ERT images of drying anywhere else in the pattern.) As mentioned above, the initial heating of this unit would have been imaged as a resistivity decrease because the effects of temperature dominate over drying effects. As heating continues, additional temperature increases and drying are generated, but the effects of drying on the resistivity differences become more important. The exact point where the resistivity begins to increase will depend on the details such as soil cation exchange capacity, saturation, and temperature as shown in Figure 22.

Immediately below this anomaly of enhanced resistivity that we attribute to drying, there is a strong anomaly of reduced resistivity. Notice that this anomaly corresponds to the depth of the sandy gravel formation, which is the target for the steam sweep. We believe this anomaly results from pore water heated directly by ohmic dissipation or indirectly by thermal conduction from the adjacent heated clays. It may also be water that was injected to maintain electrical contact between electrodes and the ground. This injected water would have been heated as it passed through the hot electrode before moving into the soil. This zone of heated groundwater appears to extend about as far as the clay dried in planes TEP9–7 and TEP9–8 but somewhat larger in planes TEP9–10 and TEP9–4.

There are two other areas in which effects of ohmic heating are observed by mid-December. The clearest is the conductive anomaly forming near TEP7 which is likely caused by heating from HW3. The lower electrode in HW3 had received 6000 kWh electrical by mid-December. The anomaly is confined to a small region in planes TEP8–7, TEP7–9, TEP7–10, and TEP7–2. In each plane, it coincides vertically with the lower steam zone and, therefore, is probably warmed water, perhaps heated as it passed through the electrode in HW3, when water was injected to maintain electrical contact to the formation.

The other anomaly is imaged as a diffuse conductive zone around HW1 in plane TEP10–6. Because this is a wide image plane (the holes are about 27 m apart), sensitivity is poor near the middle of the image, and the magnitude of resistivity change is surely underestimated toward the image center. There is no evidence of a resistive anomaly, which would be a clear sign of drying. We interpret this image as evidence for a zone of heating about 10 m in diameter around HW1, which by this time had accepted 14,500-kWh electrical in both upper and lower electrodes together.

The other principal feature observed below the water table by mid-December is a resistivity anomaly that coincides with the lower steam zone and appears to extend continuously for at least 45 meters through TEP8–10 and TEP10–5. We attribute this to the relatively resistive water injected at the heating wells to maintain electrical contact with the formation but which was not heated by passing through an electrode. This water at 167 ohm-m mixed with the groundwater, at 13 ohm-m, to produce the 10 ohm-m anomaly we imaged. The exact entry point(s) of this water cannot be uniquely determined since water was added to virtually all heating wells to improve ohmic heating performance.

Apparently wells GIW815, GIW813, and GIW814 were too far from any ERT plane to image any effects due to heating from them. Notice particularly, the lack of significant changes in TEP2–11.

Vadose Zone by Mid-December

By mid-December 27,000 kWh had been applied to the lower three HW electrodes (HW1, HW2, and HW3). During the same period, a comparable 23,500 kWh electrical had been applied to the electrodes in the vadose zone. However, the energy distribution and effects of heating seem to be somewhat different. First, and contrary to intuition, there is no evidence in the vadose zone of heating to the point of substantial drying. Rather there is an anomaly of decreased resistivity throughout much of the inner planes (TEP9–10, TEP10–7, TEP7–8, TEP8–9, TEP9–7, and TEP8–10) but extending a short distance beyond (TEP9–4, TEP10–6, TEP7–2, and TEP3–8). We interpret this as a general temperature and possibly moisture-content increases (from water being added to the heating electrodes) throughout this area. In some planes, the anomaly coincides with a permeable zone (e.g., TEP9–7), in some with a clay-rich unit (e.g., TEP8–10), and in some with both types of lithologies (e.g., TEP7–8). There is a strong resistive anomaly near the top or just above many of the inner planes and in TEP9–4. We do not know the cause of this anomaly.

Saturated Zone by Early January

By January 5–6, at the end of the ohmic heating phase, the effects of heating in the saturated zone have changed only a little from the mid-December images. The drying zone centered on TEP9 has grown a little larger. Likewise the region of warmed water in the target steam zone directly beneath is larger and extends over into plane TEP7–8. There is a small clayey silt unit, at 34-m depth in the TEP7–1 plane near TEP7, that appears to be dehydrating. However, the anomalous region is not detected in the other planes adjacent to TEP7. There is also a new conductive anomaly extending through TEP2–11. Since it is some distance from any electrode array, it is likely due to advected and slightly warmed water through one of the many permeable units in that area.

We can use the model calculations shown in Figure 22 to estimate the amount of drying occurring close to TEP9. Figure 24 shows that the temperature measured in the well is approximately 40°C at the depth corresponding to the resistive anomaly, and the magnitude of the resistive anomaly ranges between 8 and 10 ohm-m. Using the curves in Figure 22, we estimate that the liquid saturation of the formation would be about 0.4. Note that this analysis assumes that the only changes in the electrical resistivity of the water in the clay layer during ohmic heating are caused by temperature increases. As pointed out earlier, the heating electrodes were flooded with water that was 12–13 times more resistive that the native groundwater. If significant volumes of this water penetrated the clay layer, a portion of the observed resistivity increases would be caused by the increases in water resistivity. In this case, the liquid saturation of 0.4 would be a lower bound estimate for the clay saturation.

The major difference between the mid-December and early January images are in the resistive anomaly associated with the lower steam zone. If this anomaly is caused by the relatively resistive water added to each heating electrode, the later data show that it has pervaded most of the site and is now in planes TEP2–11 (putting it off site) and TEP1–7.

<u>Vadose Zone by early January</u>

Comparison of the mid-December and late January images supports the conclusion that for the most part, heating continued to drive resistivity down (temperatures went up), but the general distribution of the anomalies is similar at the two times. The major difference is in TEP2–11, which has developed a major conductive anomaly (likely warmed water) adjacent to TEP2 at the level of the gravely units. However, the target must be strongly 3 dimensional since only weak anomalies show up in adjacent TEP2–8 and TEP2–7.

Lessons Learned: Performance of the ERT Technique

1) The most important lesson learned as a result of this demonstration is that the ERT technique is sufficiently developed to produce near-real-time images showing the effects of steam invasion and ohmic heating. The experience gained showed that it was possible to produce on a sustained basis ERT images within one hour of the data being collected. This test demonstrated that ERT tomographs, used in combination with other data such as temperature, can be used reliably by the decision-makers to monitor and control the progress of subsurface remediation.

2) The number of tomography planes that could be sampled during one shift was generally 7 or 8, the ability to do twice as many planes would have been desirable. The rate limiting factor was the speed with which the automatic data acquisition system can collect data. For sites with areal extent equal to or greater than the site described here, a faster data acquisition system will be desirable or required.

3) We have also learned that resistivity differences caused by steam injection and ohmic heating are caused by several factors including temperature changes, liquid saturation changes, and changes in the ionic content of the water in the pore spaces of the formation. These different effects can make the interpretation of the ERT images somewhat complex, and can require the use of models such as the one described in the subsection "Relative effects of temperature, water saturation and fluid conductivity on resistivity changes caused by steam injection." The results from such a model used with independent data, such as temperature, can be used to infer the root cause for the resistivity differences observed. The models can also be used to estimate parameters of interest, such as liquid saturation based on measurements of temperature and electrical resistivity. Our experience also suggests that the initial liquid saturation of the vadose layers needs to be independently determined to provide similar estimates for the vadose zone.

4) During the course of steam injection, there were several instances in which the quality of the ERT tomographs degraded. This was an intermittent problem without an obvious cause. This problem only occurred with data from boreholes

TEP1, TEP7, and TEP10. One suspicion is that one or more of the above-ground treatment-plant hardware generated intermittent EM fields that coupled into the ERT cables thereby corrupting the measurements. To evaluate this suspicion, we needed to collect data while various pieces of treatment-plant hardware were systematically turned on and then off. Systematic shutdown of treatment-plant hardware was not possible during steam injection owing to operational requirements. Another possibility is that large self-potential fields associated with subsurface liquid flow caused DC voltages, which occasionally went beyond the range for which the measurement system could correct. This intermittent problem occurred in boreholes near the center of the pattern where the hydraulic gradients and liquid flow were largest. Thus, self-potential fields in this area would be the strongest.

Yet another possibility is that the problem was not caused by noise-corrupted data but was caused by one of the assumptions made by the inversion algorithm. The algorithm assumes that the resistivity structure is two-dimensional, i.e., resistivity may vary along the vertical and horizontal axes but remains constant along the orthogonal direction to the image plane. This assumption is generally valid in layered media under ambient conditions. However, the Dynamic Stripping processes probably caused three-dimensional changes in the resistivity structure that may have invalidated this assumption and caused degradation of the ERT images.

5) The number of boreholes (and related borehole separation) used by ERT to monitor the Dynamic Stripping process requires compromises between two competing requirements: 1) reduced drilling costs, which demands fewer boreholes and greater borehole separation, and 2) more boreholes with smaller borehole separation to achieve sufficient sensitivity and resolution with ERT. The experience gained shows that ERT image planes with aspect ratios of 1:2 (width to height) gave the best resolution and sensitivity. Image planes with aspect ratios of approximately 1:1.2 appeared to have just enough sensitivity to resistivity changes near the middle of the image where the least sensitivity is expected. This experience suggests that a minimal aspect ratio of 1:1.2 is required for crosshole ERT detection of resistivity changes caused by the Dynamic Stripping process.

Summary and Conclusions

We used electrical resistance tomography to monitor changes in the soil's electrical resistivity caused by the Dynamic Underground Stripping Project at LLNL. Our objective was to test the capabilities of this technique to map (in near-real time) the progress of two in situ thermal processes: steam injection and ohmic heating. Measurements were made over a seven-month period: before and during ohmic heating; and before, during, and after steam injection. A total of twenty-one vertical planes were monitored during the course of the test. Fifteen of these planes were sampled every other day; the remaining planes were sampled less frequently.

The efficacy of ERT to detect the effects of the both in situ thermal processes was evaluated by comparing the tomographs with other independent data: lithologic columns and temperature profiles. On the basis of these comparisons, inferences were made on the progress of each thermal process throughout the site. Conclusions based on the analysis of the ERT data are as follows:

1) ERT mapped changes in soil resistivity that were caused by both thermal processes. The tomograph information was used to track the spatial and temporal progress of both in situ thermal processes. During steam injection, the tomographs show decreases in resistivity as high as 60%. We propose that the resistivity decreases are caused by the heating of the original groundwater and soil by steam and hot steam condensate, resulting in increasing the clay-exchange cation conductance and decreasing electrolyte resistivity. The resistivity decreases caused by heating during steam injection were somewhat counterbalanced by the injection of electrolyte with a higher resistivity than the native groundwater. The steam condensate mixed with the native groundwater caused relatively minor reductions in the magnitude of the resistivity decreases caused by heating.

2) The resistivity structure observed in baseline ERT tomographs compare favorably with lithologic logs based on geologists' descriptions of core samples. In general, the least resistive sections of the tomographs correlate with units with higher clay content, such as silts and clay layers; the most resistive parts of

the tomographs correlate with sand and gravel units. The ERT tomographs can be used to map the lateral continuity of the layers.

3) The ERT tomographs were produced by automated data-collection and data-processing systems that allowed tomographs to be processed in near real time, generally within twenty minutes after each data set was collected. Reliable and timely process control decisions can be based on the ERT tomographs and other data, such as temperature logging and data from tiltmeter arrays. The tomographs show that steam flow occurred preferentially toward the extraction wells.

We conclude from our results that ERT techniques can be used to monitor the progress of a steam remediation process in geologic environments similar to the one described herein. The results have shown that the technique can be used to estimate the location and size of the invaded zone as well as its evolution over time. The experience gained from this test has been used to optimize our data interpretation process so that images can be generated within minutes after the data are collected.

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